ATTACHMENT III

CMAQ MODELING AND EVALUATION

MARICOPA ASSOCIATION OF GOVERNMENTS

OFFICE MEMORANDUM

DATE: February 22, 2008

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FROM: Huiyan Yang, Air Quality Engineer II

SUBJECT: **Simulation of Ozone for the Maricopa Nonattainment Area by Using the EPA Models-3/Community Multiscale Air Quality Modeling System (CMAQ) and Comparison with the Results of the Comprehensive Air Quality Model with extensions (CAMx)**

The CAMx model was used to simulate ozone for three episodes for the Eight-Hour Ozone Plan for the Maricopa Nonattainment Area (MAG, 2007). This plan was submitted to the U.S. EPA in June 2007. The reason to conduct CMAQ simulations after doing CAMx modeling is to provide a source of ancillary model assessments for the same ozone episodes, and therefore to substantiate the attainment demonstration for the ozone season in 2008.

The U.S. EPA Models-3/CMAQ modeling system is a third generation air quality modeling tool for the regulatory and science communities. The CMAQ modeling system includes interface processors to incorporate the outputs of meteorology and emission models, and preprocessors to prepare the requisite input information for initial and boundary conditions and photolysis rates. The information is then input to the CMAQ Chemical Transport Model (CCTM), which performs chemical transport modeling for multiple pollutants on multiple scales (U.S. EPA, 1999). The latest release of CMAQ version 4.6 as of September 30, 2006 was used in this model performance study.

This report is organized into four sections. Section 1 describes the modeling domain and the chemical mechanism. Section 2 introduces how the model input data sets were prepared. Section 3 describes the results of the CMAQ simulation including an evaluation of the CMAQ results against observations and comparisons with the former CAMx simulation. Section 4 summarizes the results of the model performance evaluations of the CMAQ and CAMx models.

1. Model Setup

1.1 Modeling domain

The CMAQ modeling grids are based on the Lambert Conformal Projection (LCP) modeling domain of the Fifth Generation Mesoscale Model (MM5) that was used to develop meteorology for CAMx. The rationale is that CMAQ will use the same meteorology data as was used in the CAMx modeling. The grid parameters of the MM5 and CMAQ modeling domains are listed in Table 1 (Emery and Koo, 2007). The central

latitude and longitude of the MM5 LCP coordinate are 34˚N and 111˚W, and the conic true latitudes are 45˚N and 33˚N. The boundaries of the CMAQ domains are slightly inset several grid cells on each side from the boundaries of the MM5 domains. This was done, as suggested in the Meteorology-Chemistry Interface Processor (MCIP) guidance, as a method to remove boundary "noise" near the MM5 boundaries.

Table 1. The MM5 and CMAQ Modeling Domains

The MM5 Modeling Domains		
Grid	**Grid Size**	**LCP range (km)**
36-km grid	64 by 49	(-1134, -864) to (1134, 864)
12-km grid	118 by 91	(-810, -612) to (594, 468)
4-km grid	61 by 40	(-234, -132) to (6, 24)
The CMAQ Modeling Domains		
Grid	**Grid Size**	**LCP range (km)**
12-km grid	111 by 84	(-774, -576) to (558, 432)
4-km grid	50 by 29	(-202, -112) to (-2, 4)

Note that CAMx was run in the Universal Transverse Mercator (UTM) Zone 12, as opposed to the LCP projection used for both MM5 and CMAQ. Fortunately, the MM5 LCP projection was centered on UTM Zone 12, which allows the UTM and LCP projections to align fairly well. In fact, the 12-kilometer (km) grid CMAQ modeling domain is the same as CAMx. And there is almost a 1-for-1 grid cell match up between CMAQ and CAMx for the 4-km grid modeling domain as well, except for the 2-km (half grid) discrepancy in the south-north direction. The domain origin of CAMx in the south-north direction is -110 km (converted from UTM 3652 km northing in UTM zone 12). This 2-km discrepancy between the two modeling domains is not expected to affect the overall comparison of model performance between CMAQ and CAMx.

The vertical structure used in the CMAQ modeling is the same as used in the CAMx modeling. There are 20 layers in the 12-km grid modeling domain and 23 layers in the 4-km grid modeling domain. The top level is set at ~15 km (MAG, 2007).

1.2 Chemical mechanism

To be consistent with the chemical mechanism used in CAMx, the cb5 chemical mechanism was also used in the CMAQ simulation,. More specifically, cb5_aq is used, since cb5 alone does not include wet deposition. A total of 51 species are simulated in cb5_aq, including NO, NO_2, O_3, PAN, OH, CO, and different VOC species, etc. There are a total of 156 reactions used in cb5_aq.

It should be noted that methanol and ethanol are commented out in the CMAQ cb4 mechanism, which are included in mechanism 4 in CAMx. Since methanol and ethanol have primary emissions in the MNA 4-km gridded modeling domain, and since they are also precursors of ozone, the cb5_aq chemical mechanism that was used in the CMAQ

modeling was configured to include these two species. HONO was added to the emissions list. There are several primary species (ALDX, IOLE, TERP, and ETHA) that are included in CMAQ's cb5 chemical mechanism that are not included in CAMx's mechanism 4 (chemical mechanism). However, this should not affect the results of comparing the performance of the two models since there are no emissions for these species in the MNA 4-km grid modeling domain.

Preliminary analysis shows that cb5_aq produces 1 or 2 ppb more ozone than cb4_aq. Thus, the conclusions that were based on cb5_aq are not expected to change when the chemical mechanism changes to cb4_aq. The results presented in this report are based on cb5_aq.

1.3 Advection scheme

To be consistent with the CAMx modeling, the Piecewise Parobolic Method (ppm) for advection was also used in the CMAQ modeling. An experiment using the global mass-conserving scheme (yamo) is described in a separate report. The results from the global mass-conserving scheme are similar to the results described in this report.

2. Model input data

For the original CAMx modeling performed for the MAG Eight-Hour Ozone Plan, the original input data sets of meteorology, emissions, initial condition (IC) and boundary condition (BC) had been reviewed for accuracy and consistency (MAG, 2007). These same input files were used in the CMAQ modeling.

The MM5 meteorology was processed to the CMAQ I/O API format by using MCIP. The CAMx binary format emissions and IC/BC for the 12-km grid modeling domain were converted to the CMAQ format by using processors provided by ENVIRON. The ICON and BCON pre-processors were used to extract IC/BC for the 4-km grid modeling domain from the modeling results of the 12-km grid modeling domain.

The photolysis rate preprocessor (JPROC) was used to produce a clear-sky photolysis rate look-up table. Default model settings or parameters were used for this calculation. The following specific parameters were used: (1) Ultra-violet (wave length < 400nm) albedo was set to 0.05, (2) Aerosol/haze was uniformly set to have an optical depth of ~0.32, and (3) The World Meteorology Organization (WMO) 1981 monthly average total ozone column data was used and these data range from ~280 to 370 Dobson units (DU) for June, July and August in the latitudinal bands between 30°N and 40°N.

3. Results

The simulated surface ozone concentrations in the MNA 4-km grid modeling domain are discussed in the following sections. The first three days of each episode were used to spin up the model to reduce the potential errors introduced through the initial conditions. These spin-up days were not included in the analysis. The last day in each episode was missing due to the conversion from the Greenwich Mean Time (GMT) convention that was used in CMAQ modeling to the Mountain Standard Time (MST) convention used in CAMx modeling (MST is seven hours behind the GMT). Note: in this report, all references to time are in MST units.

3.1 Evaluation against observations

One-hour (hourly average) ozone observational data were obtained from EPA and the data were reorganized by MAG for use in evaluating the CMAQ's model performance. This was the same observational data set used in the CAMx evaluation. After converting the CMAQ results to the CAMx binary format, the CAMx evaluation tools were used to analyze the CMAQ results. The CAMx results cited for comparison were presented in MAG's Eight-Hour Ozone Attainment plan (MAG, 2007).

3.1.1 The June 2002 episode (June 3 to June 6)

Figure 1 depicts the time series of simulated one-hour ozone concentrations overlaid with the observed one-hour ozone values from 21 ozone monitoring sites located in the MNA. The model predictions are fairly consistent with observations on the timing of net positive ozone production, which is approximately 7 am. The maximum ozone occurs between 3 and 7 pm, and the minimum is usually reached at approximately 6 am. The diurnal cycle is stronger at sites located closer to central Phoenix, such as the Phoenix sites WP, NP, CP, SUPR; the Tempe site TEMP; and the MESA site ME. These sites sometimes have the lowest ozone level of approximately 1 ppb at night, since these sites are more heavily influenced by urban conditions.

The diurnal variation is less prominent at sites farther away from central Phoenix, such as the Scottsdale site PP, and the Cave Creek sites CC and HM. These sites are more heavily influenced by the background ozone or transported ozone. The variation trend of diurnal cycles in the model is consistent with the observations, which suggests that the local production and long-range transport of ozone, and therefore the spatial distribution, are generally captured in the model.

CMAQ overpredicted ozone levels on June 5th and 6th. ENVIRON staff suggested that the dry deposition schemes, RADM and M3DRY, should be tested and compared (Emery, personal communication, 2007) to determine if they are involved in the over-prediction. It turned out the two dry deposition schemes produced almost the same results. This bolsters the argument that the over-prediction of ozone in CMAQ is possibly caused by its strong vertical mixing scheme, as was suggested by ENVIRON (Emery, personal communication, 2007) and Timin et al. (2007). In contrast, the CAMx model used a weak vertical mixing scheme OB70 and it performed much better.

However, it is out of the scope of this project to conduct a test of different vertical mixing schemes in CMAQ due to the constraints of module implementation. Another major inconsistency between model prediction and observations occurs at night. This may be a result of the strong vertical mixing scheme used in the CMAQ model causing NOx at the surface to be heavily diluted and subsequently leading to weak ozone destruction.

The time series of the eight-hour (eight-hour average) ozone is depicted in Figure 2. This curve is relatively smooth when compared with a similar curve for one-hour ozone, and the peak hour is shifted to approximately 12 pm. The agreement of CMAQ's simulated eight-hour ozone with observations is generally better in the morning than in the afternoon, when there is an over-prediction, especially at sites close to central Phoenix. June 6th is an exception, since the over-prediction of one-hour ozone occurs in the morning for most sites on this day. The sites farther away from central Phoenix are generally better predicted. Figure 3 gives the scatter plot of eight-hour ozone levels. As expected, the over-prediction occurs mainly for ozone concentrations lower than 60 ppb, which typically occurs at night. The predicted ozone values are more consistent with the observations at high ozone levels during the day.

The statistical evaluation indices of CMAQ and CAMx model performance are presented in Table 2. EPA's recommended goals for model performance are: (1) Unpaired peak prediction accuracy (UPPA) is < ± 20%, (2) Normalize Bias (NB) is < ±15%, and (3) Normalized Error (NE) is < 35% of the average prediction. The modeling evaluation index results that are outside of the range of the EPA goals are highlighted in red bold text in Table 2. The definitions for all the statistical indices are discussed in MAG's Eight-Hour Ozone Attainment Plan (MAG, 2007).

Table 2 shows that indices with 60 ppb thresholds are generally within the range of the EPA goals, except for the UPPA and NB on June 3rd when there was no exceedance of the daily maximum eight-hour ozone. The NB and NE, without thresholds, for both the one-hour and eight-hour ozone are outside the range of EPA goals due to the CMAQ model's over-prediction at night (previously described in this section). The UPPA is the same with or without a threshold, since the peak ozone is above the threshold of 60 ppb.

Table 2. Summary of the Statistical Modeling Evaluation for the June 2002 Episode

	6/3	6/4	6/5	6/6
One-Hour with a 60 ppb threshold (CMAQ)				
Unpaired Peak Prediction Accuracy (%)	**-22.5**	-5.8	8.4	11.6
Normalized Bias (%)	**-22.3**	-2.5	11.9	10.2
Normalized Error (%)	22.4	11.3	14.7	12.5
One-Hour with a 60 ppb threshold (CAMx)				
Unpaired Peak Prediction Accuracy (%)	**-25.6**	1.4	1.7	5.1
Normalized Bias (%)	**-28.9**	-5.5	5.1	-0.5
Normalized Error (%)	28.9	10.0	10.3	8.9
Eight-Hour with a 60 ppb threshold (CMAQ)				
Unpaired Peak Prediction Accuracy (%)	**-30.7**	-4.4	8.9	6.4
Normalized Bias (%)	**-19.8**	0.8	13.2	12.3
Normalized Error (%)	19.9	9.9	14.1	13.2
Eight-Hour with a 60 ppb threshold (CAMx)				
Unpaired Peak Prediction Accuracy (%)	**-28.6**	1.0	7.7	-1.8
Normalized Bias (%)	**-25.1**	-3.3	7.8	0.2
Normalized Error (%)	25.1	7.9	9.8	8.0
Note: Modeling Evaluation Indices outside of EPA's goals are shown in bold red font.				

3.1.2 The July 2002 episode (July 8 to July 13)

The time series of one-hour and eight-hour ozone concentrations are plotted in Figure 4 and Figure 5, respectively. Figure 6 contains a scatter plot of the results. Table 3 lists the results of the statistical evaluation. The general feature of the diurnal variation of ozone for the July 2002 episode is similar to the June 2002 episode, except when it was under-predicted in the July 2002 episode (mainly July 9th to July 12th).

Table 3. Summary of the Statistical Modeling Evaluation for the July 2002 Episode

	7/8	7/9	7/10	7/11	7/12	7/13
One-Hour with a 60 ppb threshold (CMAQ)						
Unpaired Peak Prediction Accuracy (%)	-4.1	**-28.1**	**-34.6**	**-36.5**	**-29.0**	-5.5
Normalized Bias (%)	-12.7	**-30.6**	**-32.5**	**-38.7**	**-30.6**	**-19.1**
Normalized Error (%)	14.7	30.8	32.7	**38.8**	30.7	19.5
One-Hour with a 60 ppb threshold (CAMx)						
Unpaired Peak Prediction Accuracy (%)	12.4	-11.4	-7.6	-9.0	-10.8	1.5
Normalized Bias (%)	-4.4	**-23.8**	**-20.3**	**-31.0**	**-22.4**	**-21.4**
Normalized Error (%)	11.6	25.1	26.1	32.2	23.1	22.0
Eight-Hour with a 60 ppb threshold (CMAQ)						
Unpaired Peak Prediction Accuracy (%)	-9.1	**-29.7**	**-35.0**	**-34.6**	**-28.1**	-9.4
Normalized Bias (%)	-12.5	**-31.4**	**-33.6**	**-37.1**	**-30.4**	-14.8
Normalized Error (%)	12.6	31.4	33.6	**37.1**	30.5	14.8
Eight-Hour with a 60 ppb threshold (CAMx)						
Unpaired Peak Prediction Accuracy (%)	2.5	-17.0	-16.9	**-20.6**	-17.0	-8.0
Normalized Bias (%)	-5.8	**-25.7**	**-22.3**	**-30.1**	**-23.4**	**-16.3**
Normalized Error (%)	9.0	25.8	23.8	30.4	23.5	16.4
Note: Modeling Evaluation Indices outside of EPA's goals are shown in bold red font.						

A close inspection of Figure 4 reveals that when CMAQ's worst under-prediction occurred on July 10th and 11th, it was wide spread over sites located in or near the central Phoenix (e.g., Phoenix sites MV, WP, CP, SURP, and NP). In contrast, the predicted ozone is slightly more consistent with observations at many sites away from the Phoenix urban core (e.g., Surprise SU, at Scottsdale PP, at Fountain Hills FH, and at Rio Verde RV). However, there is serious under-prediction again at the remote sites at Palo Verde PALV and at Cave Creek HM.

The emissions inventory used in MAG's Eight-Hour Ozone Plan indicated that the major NOx emission sources are concentrated in and around central Phoenix, while the VOC emission sources are more scattered in the 4-km grid modeling domain (MAG, 2007), since on-road mobile sources are the dominant NOx emissions source, and biogenic sources are the dominant VOC emissions source. A previous study found that the Phoenix urban core is VOC sensitive, while the area outside of the urban core is NOx sensitive (MAG, 2007). Given the above evidence, MAG proposes that the simulated MM5 wind on July 10th and 11th may be too weak to transport enough NOx out from the urban core, which renders the predicted ozone to be lower than the observed ozone in

both the urban core and at remote sites. In addition, the weak winds may also have reduced the transport of ozone to remote areas. Another possible explanation is that the vertical mixing scheme used in CMAQ may not be strong enough to dilute the surface NOx or VOC in order to reach optimum ozone production. Further tests will be made to confirm this hypothesis and to improve the model's performance.

3.1.3 The August 2001 episode (August 5 to August 10)

The time series of one-hour and eight-hour ozone are plotted in Figure 7 and Figure 8, respectively. Figure 9 contains a scatter plot of the results. Table 4 lists the results of the statistical evaluation. Figures 7 and 8, and Table 4 show that there is an even worse under-prediction of ozone in the August 2001 episode than in the July 2002 episode, since the serious under-prediction occurs throughout the modeling domain. The possible reason is again suspected to be the MM5 meteorology, given the similar pattern of under-predictions in both CMAQ and CAMx.

Table 4. Summary of the Statistical Modeling Evaluation for the August 2001 Episode

	8/5	8/6	8/7	8/8	8/9	8/10
One-Hour with a 60 ppb threshold (CMAQ)						
Unpaired Peak Prediction Accuracy (%)	**-38.6**	**-37.0**	**-24.7**	**22.3**	**-30.3**	**-27.0**
Normalized Bias (%)	**-49.9**	**-38.5**	**-27.9**	**-21.6**	**-37.0**	**-34.8**
Normalized Error (%)	**49.9**	**38.6**	28.0	29.2	**37.0**	**35.4**
One-Hour with a 60 ppb threshold (CAMx)						
Unpaired Peak Prediction Accuracy (%)	-17.6	-13.0	1.4	**47.4**	**-24.7**	-18.6
Normalized Bias (%)	**-44.9**	**-28.0**	**-21.4**	**-20.3**	**-38.7**	**-32.7**
Normalized Error (%)	**45.0**	28.8	22.4	33.3	**38.7**	34.6
Eight-Hour with a 60 ppb threshold (CMAQ)						
Unpaired Peak Prediction Accuracy (%)	**-38.2**	**-31.2**	**-27.2**	7.4	**-30.8**	**-24.9**
Normalized Bias (%)	**-48.5**	**-38.2**	**-27.5**	**-17.1**	**-37.0**	**-35.2**
Normalized Error (%)	**48.5**	**38.2**	27.5	18.5	**37.0**	**35.2**
Eight-Hour with a 60 ppb threshold (CAMx)						
Unpaired Peak Prediction Accuracy (%)	**-22.2**	-12.1	-12.5	17.2	**-24.8**	-13.7
Normalized Bias (%)	**-43.8**	**-27.5**	**-22.4**	-12.6	**-38.9**	**-33.5**
Normalized Error (%)	**43.8**	27.5	22.4	19.0	**38.9**	33.9
Note: Modeling Evaluation Indices outside of EPA's goals are shown in bold red font						

3.2 Comparison with the CAMx results

For the June 2002 episode, the general features of ozone simulated in CMAQ are similar to those in CAMx, which can be seen in the time series of one-hour and eight-hour ozone in Figures 1 and 2. CAMx has better agreement with observations than CMAQ at sites closer to the Phoenix urban core (e.g., Phoenix sites WP, NP and CP) where the rapid ozone depletion after the peak hour is better captured. The simulation on June 5th and 6th in CAMx is more consistent with observations as well, when there is no apparent over-prediction. Some of these subtle differences are reflected in the scatter plots in Figure 3. The prediction in CAMx aligns closer to the 1:1 line with the observations, and the correlation coefficient between predictions and observations (R^2 ~ 0.66) is larger than that in CMAQ (R^2 ~0.63) as well. The statistical evaluations with 60 ppb thresholds between CAMx and CMAQ are similar (Table 2), with the scores of CAMx generally better than CMAQ. The NB and NE without thresholds in CAMx are smaller than in CMAQ, which implies that CAMx performs better at night.

For the July 2002 episode, the general features of ozone simulated in CMAQ are similar to those in CAMx (Figures 4 & 5). And it can be seen that there is an under-prediction in both simulations. The big difference is the peak prediction. The UPPA's in CAMx are almost all within the EPA range, while in CMAQ, four days are under-predicted and outside EPA's range (Table 3). Figure 6 shows that the correlation coefficient between predictions and observations in CMAQ (R^2 ~0.61) is close to the one in CAMx (R^2 ~ 0.61).

For the August 2001 episode, the general features of ozone simulation in CMAQ are similar to those in CAMx as well (Figure 7 & 8). And similar to the July 2002 episode, there is an under-prediction in both simulations in the August 2001 episode. CMAQ's under-prediction is even worse than CAMx's under-prediction (Table 4). Figure 9 shows that the correlation coefficient between predictions and observations in CMAQ (R^2 ~0.42) is smaller than the one in CAMx (R^2 ~ 0.51).

4. Summary of Results

The U.S. EPA CMAQ modeling system was used to simulate three episodes of ozone for the MNA. The CMAQ model reproduces the strong diurnal variation of ozone at sites close to the central Phoenix, with the peak hour occurring between 3 and 7 pm, and the minimum ozone levels at approximately 6 am. The diurnal variation of ozone is less prominent at sites away from central Phoenix. Evaluating CMAQ's predicted ozone levels against observed ozone levels shows that its model performance is acceptable for the June 2002 episode according to the EPA standards. However, many days in the episodes of July 2002 and August 2001 are under-predicted and outside of the EPA ranges for model performance. The comparison with the former CAMx simulation shows that the general features of the two simulations are similar, with CAMx having better overall model performance than CMAQ.

References:

Emery, C. and B. Koo, (2007), Memorandum, "Definition of a CMAQ ozone modeling grid for MAG applications", ENVIRON International Corp, Novato, CA.

Maricopa Association of Governments, (2007), "Eight-Hour Ozone Plan for the Maricopa Nonattainment Area".

Timin, B., K. Wesson, P. Dolwick, N. Possiel, S. Philips, (2007), "An exploration of model concentration differences between CMAQ and CAMx", presented at the 6th Annual CMAS Conference, Chapel Hill, NC.

U.S. EPA, (1999), "Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System", EPA/600/R-99/030.

Figure Captions:

Figure 1 Time series of simulated one-hour ozone overlaid with the observed values (dots) for the episode of June 2002. The solid line represents the CMAQ results; the dash line represents the CAMx results.

Figure 2 Time series of simulated eight-hour ozone overlaid with the observed values (dots) for the episode of June 2002. The solid line represents the CMAQ results; the dash line represents the CAMx results.

Figure 3 Scatter plots of simulated and observed eight-hour ozone in the MNA for the June 2002 episode: (a) CMAQ results; (b) CAMx results.

Figure 4 Time series of simulated one-hour ozone overlaid with the observed values (dots) for the episode of July 2002. The solid line represents the CMAQ results; the dash line represents the CAMx results.

Figure 5 Time series of simulated eight-hour ozone overlaid with the observed values (dots) for the episode of July 2002. The solid line represents the CMAQ results; the dash line represents the CAMx results.

Figure 6 Scatter plots of simulated and observed eight-hour ozone in the MNA for the July 2002 episode: (a) CMAQ results; (b) CAMx results.

Figure 7 Time series of simulated one-hour ozone overlaid with the observed values (dots) for the episode of August 2001. The solid line represents the CMAQ results; the dash line represents the CAMx results.

Figure 8 Time series of simulated eight-hour ozone overlaid with the observed values (dots) for the episode of August 2001. The solid line represents the CMAQ results; the dash line represents the CAMx results.

Figure 9 Scatter plots of simulated and observed eight-hour ozone in the MNA for the August 2001 episode: (a) CMAQ results; (b) CAMx results.
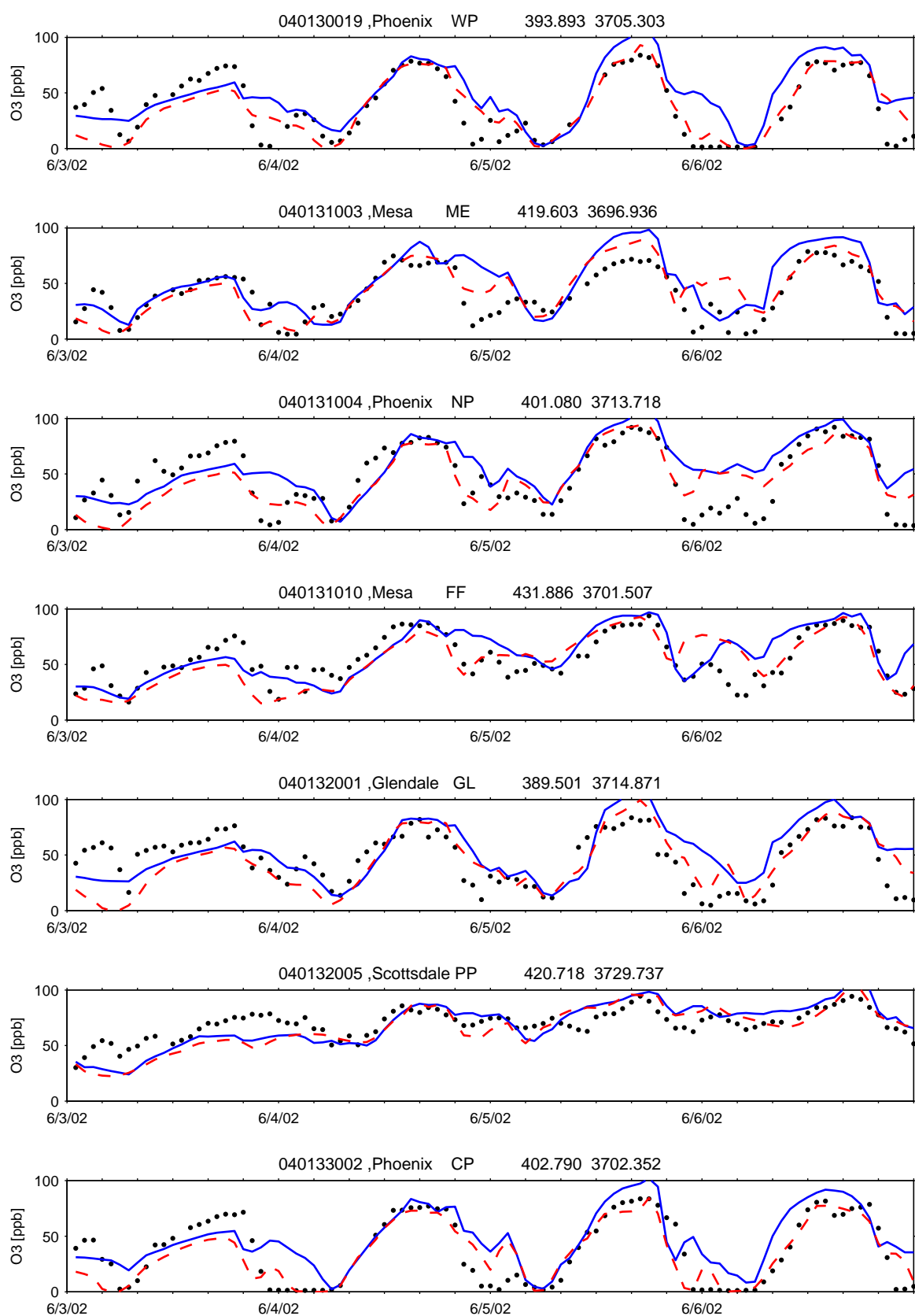
Figure 1(a).One−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx
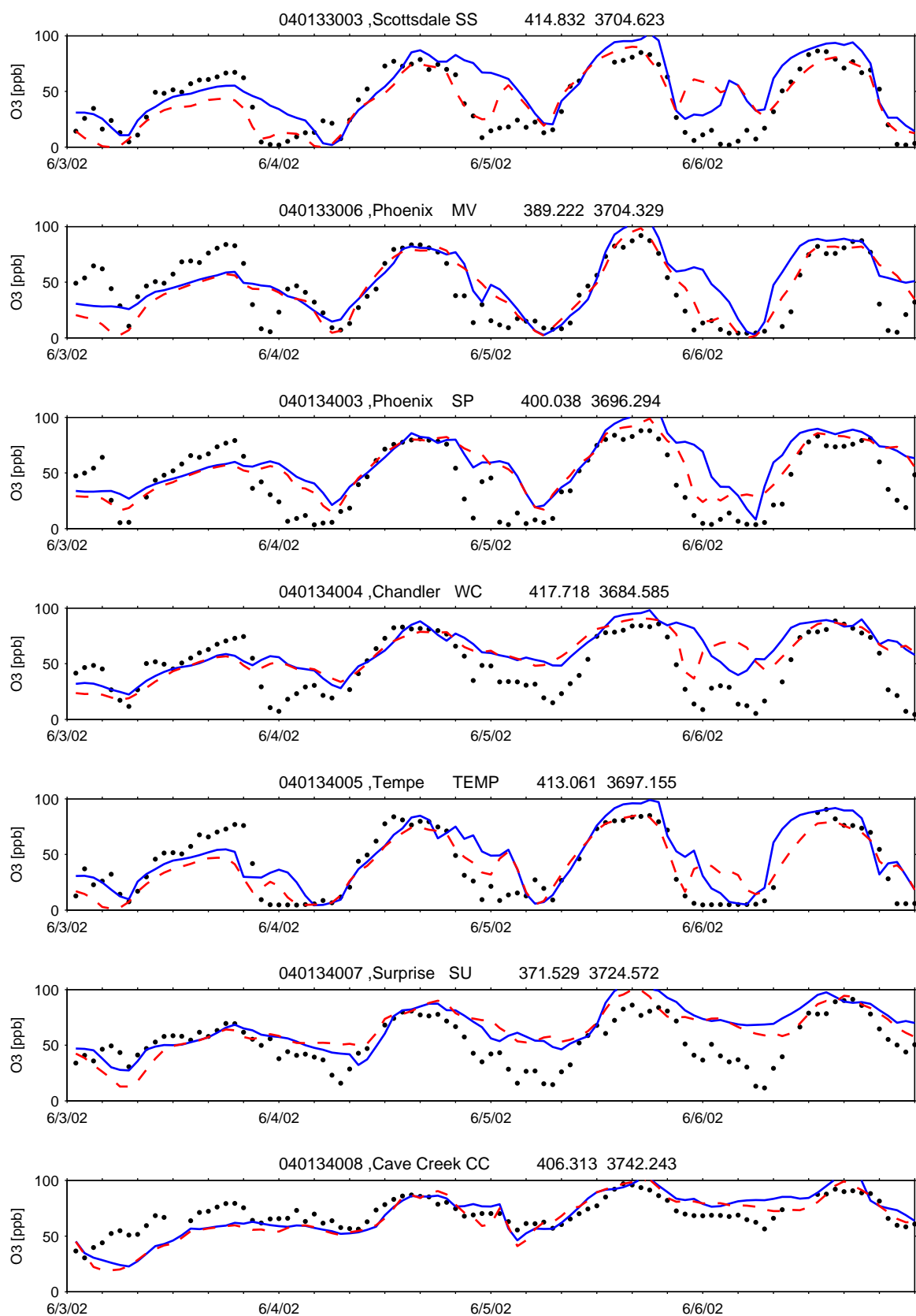
Figure 1(b).One−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx
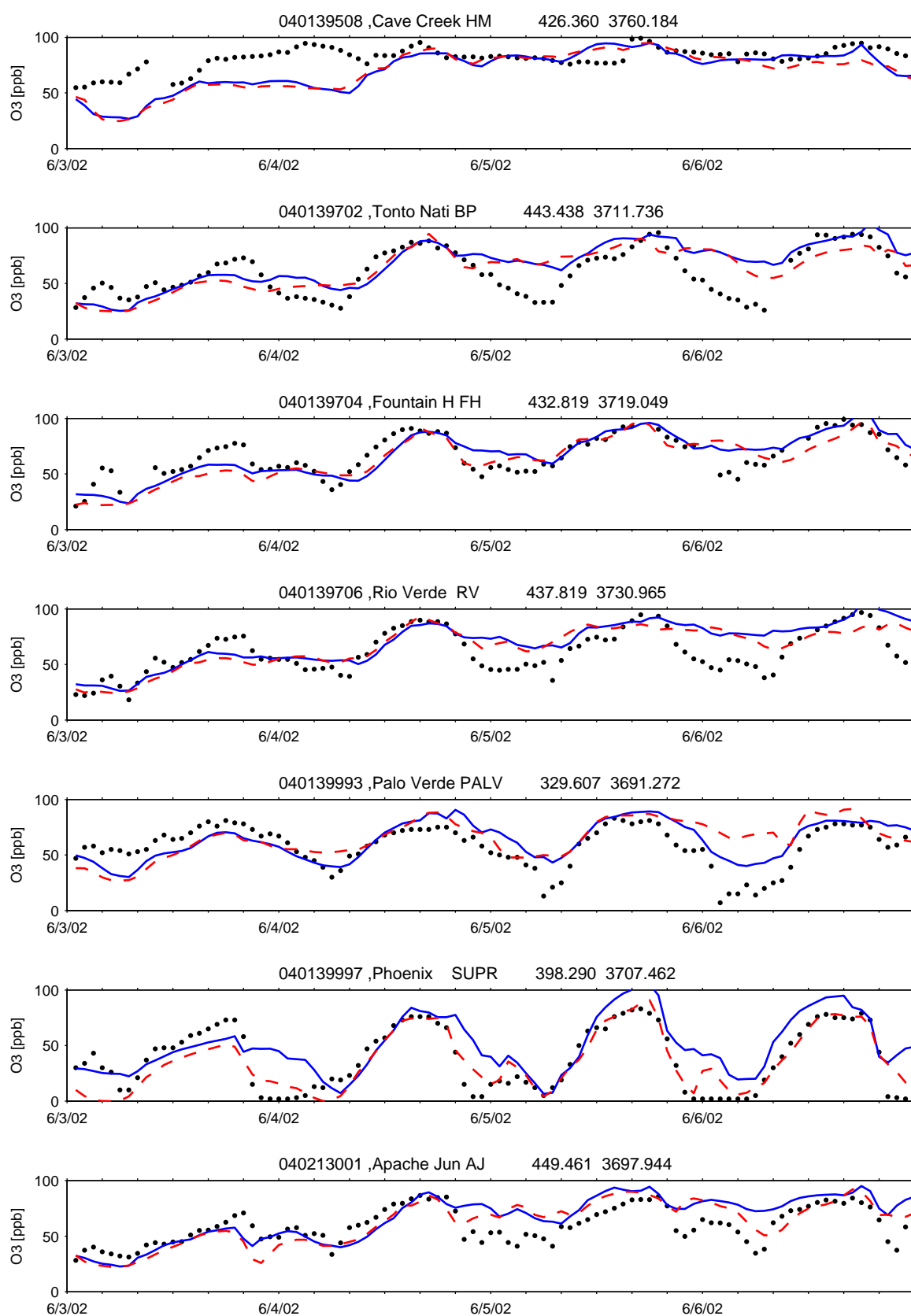
Figure 1(c).One−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx
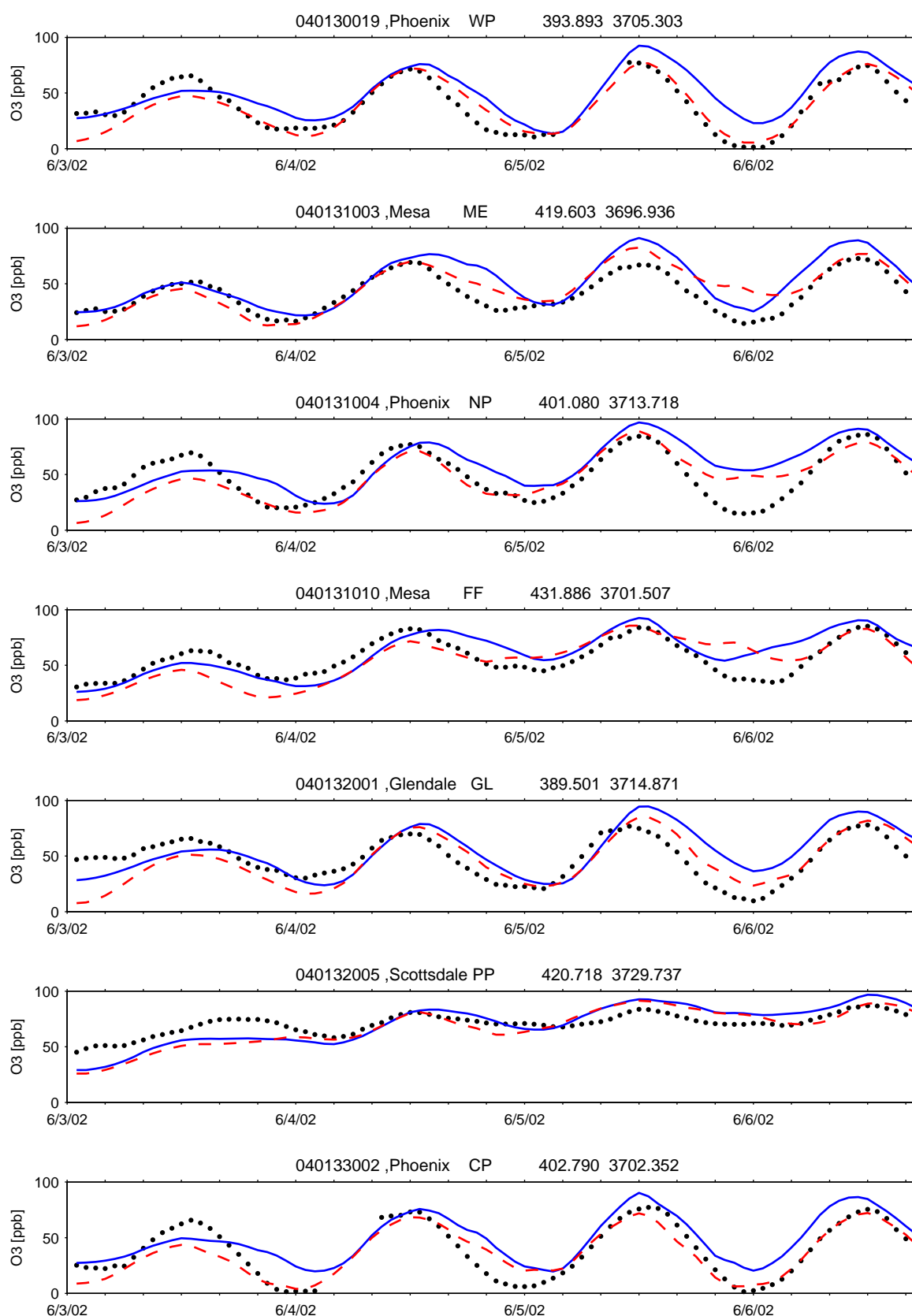
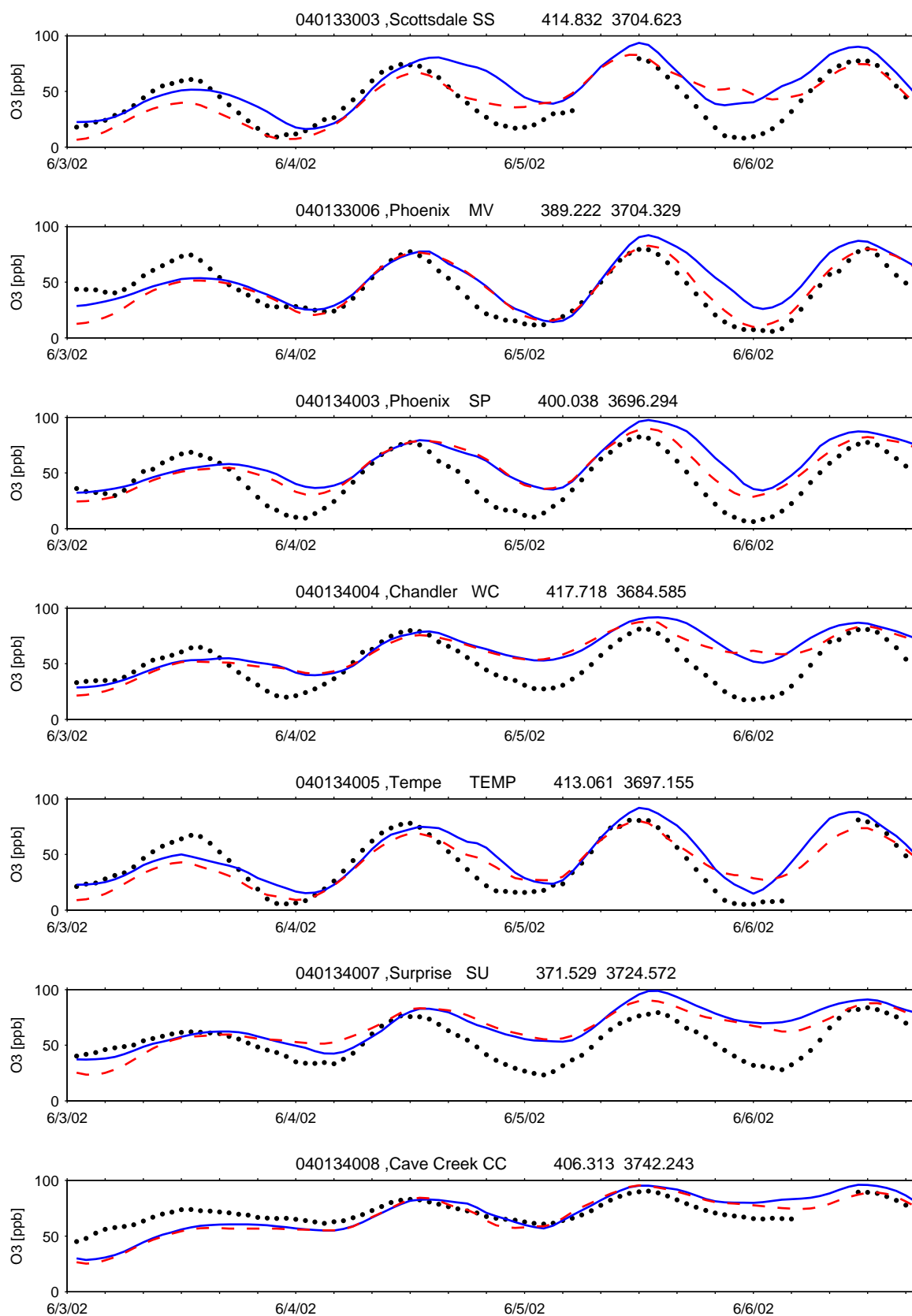Figure 2(a).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 2(b).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx
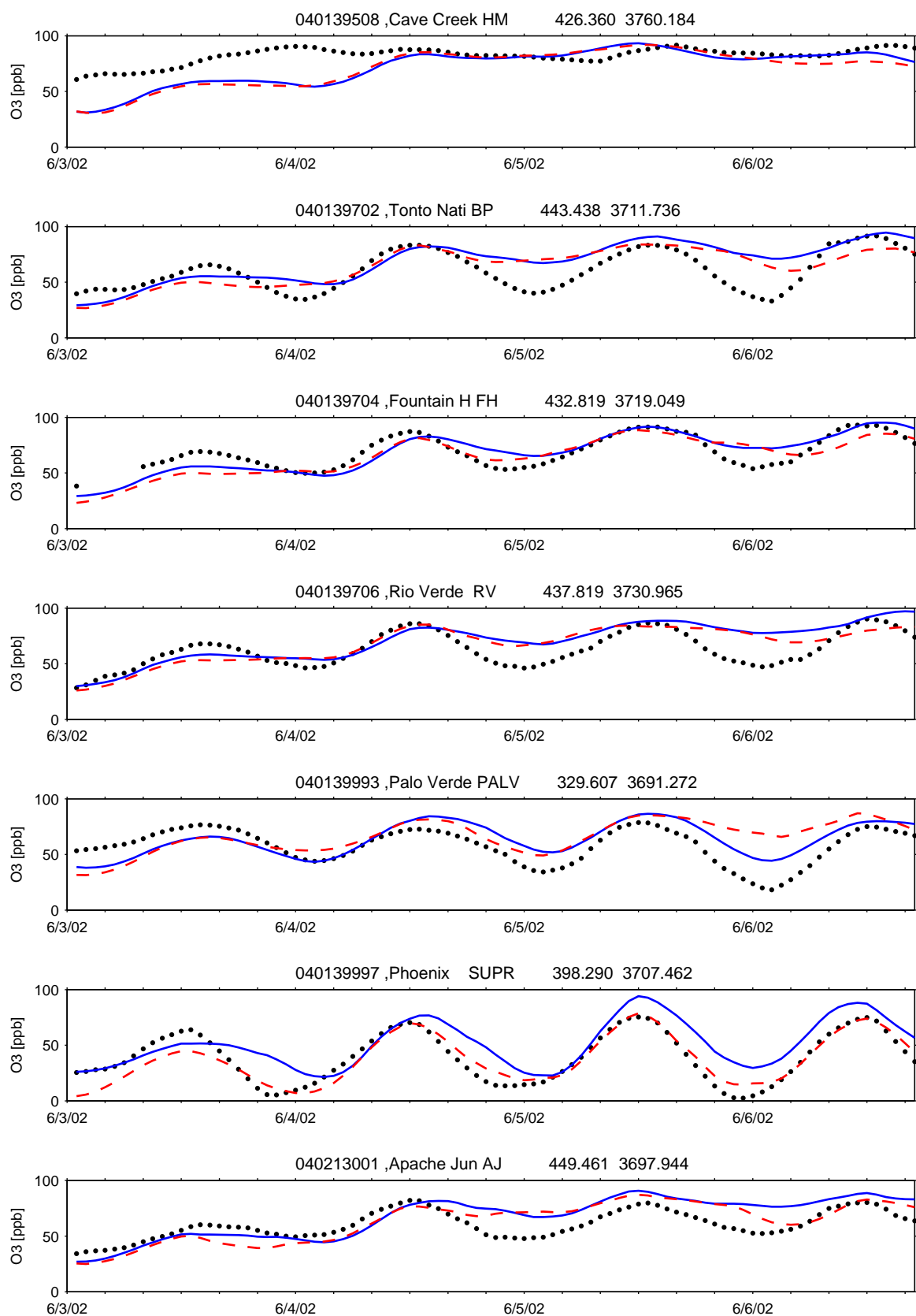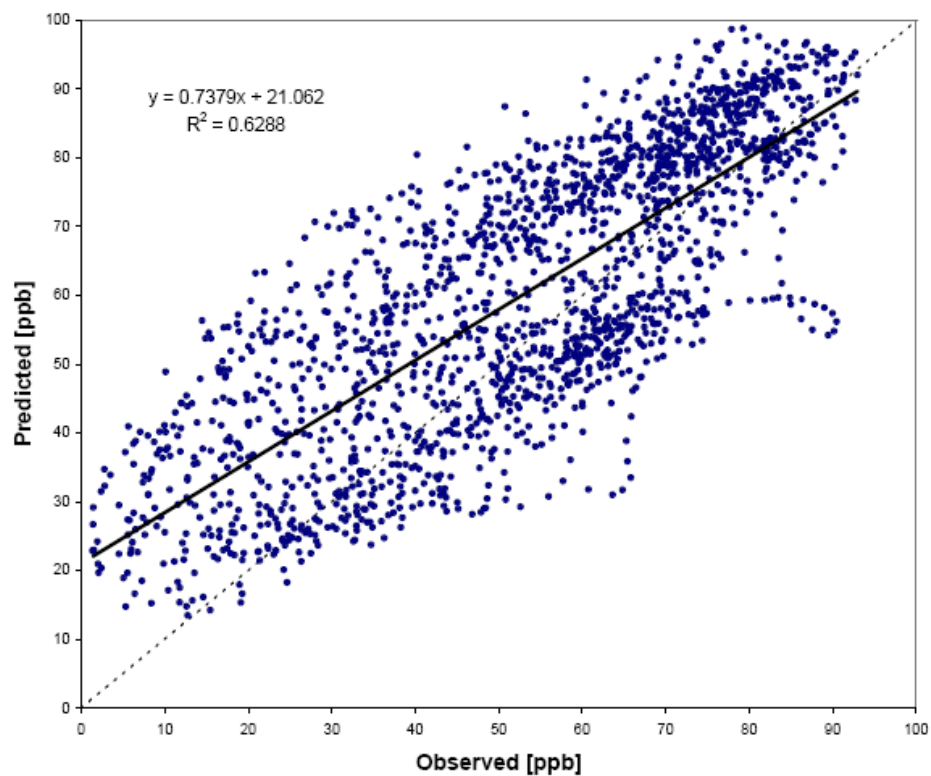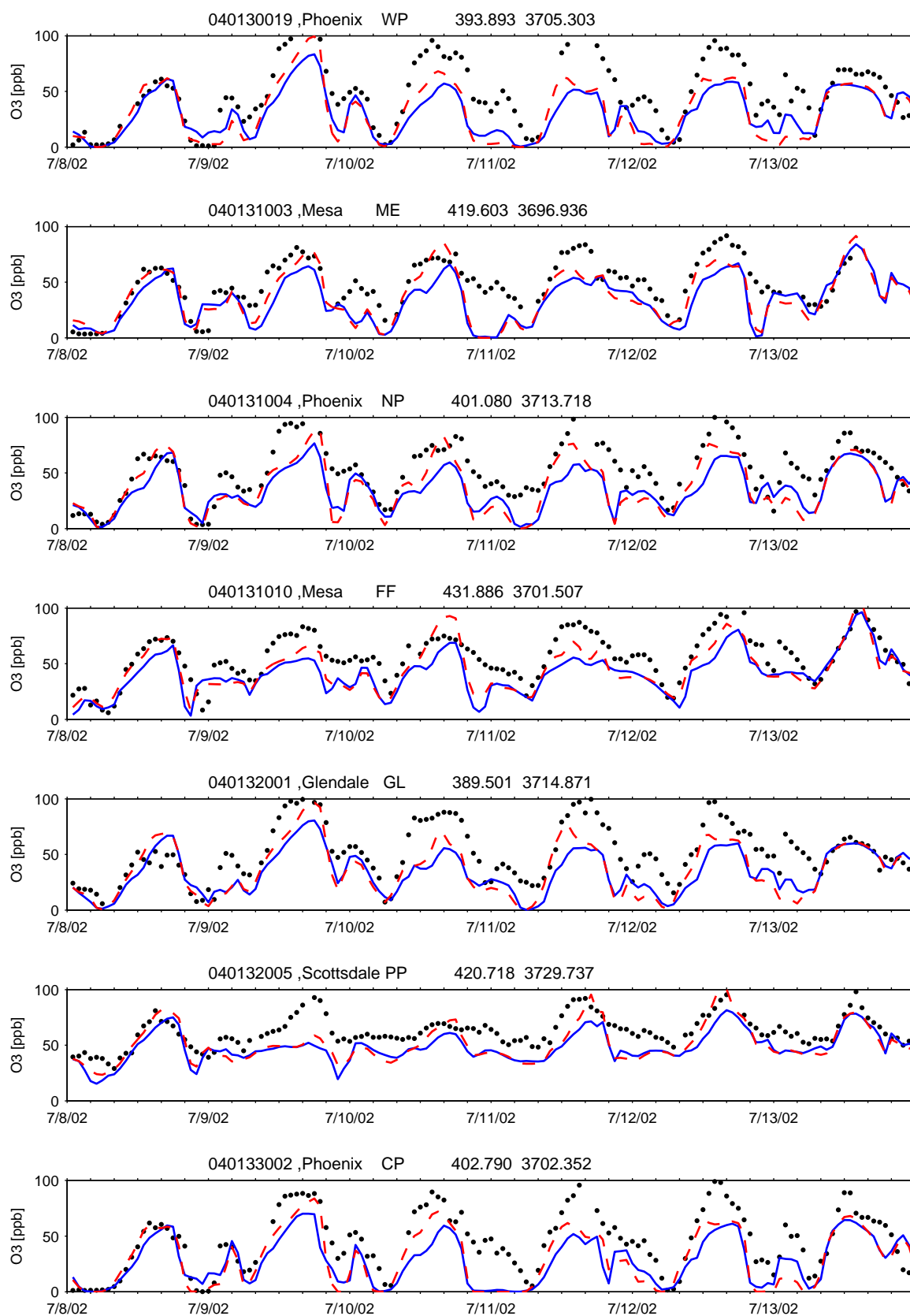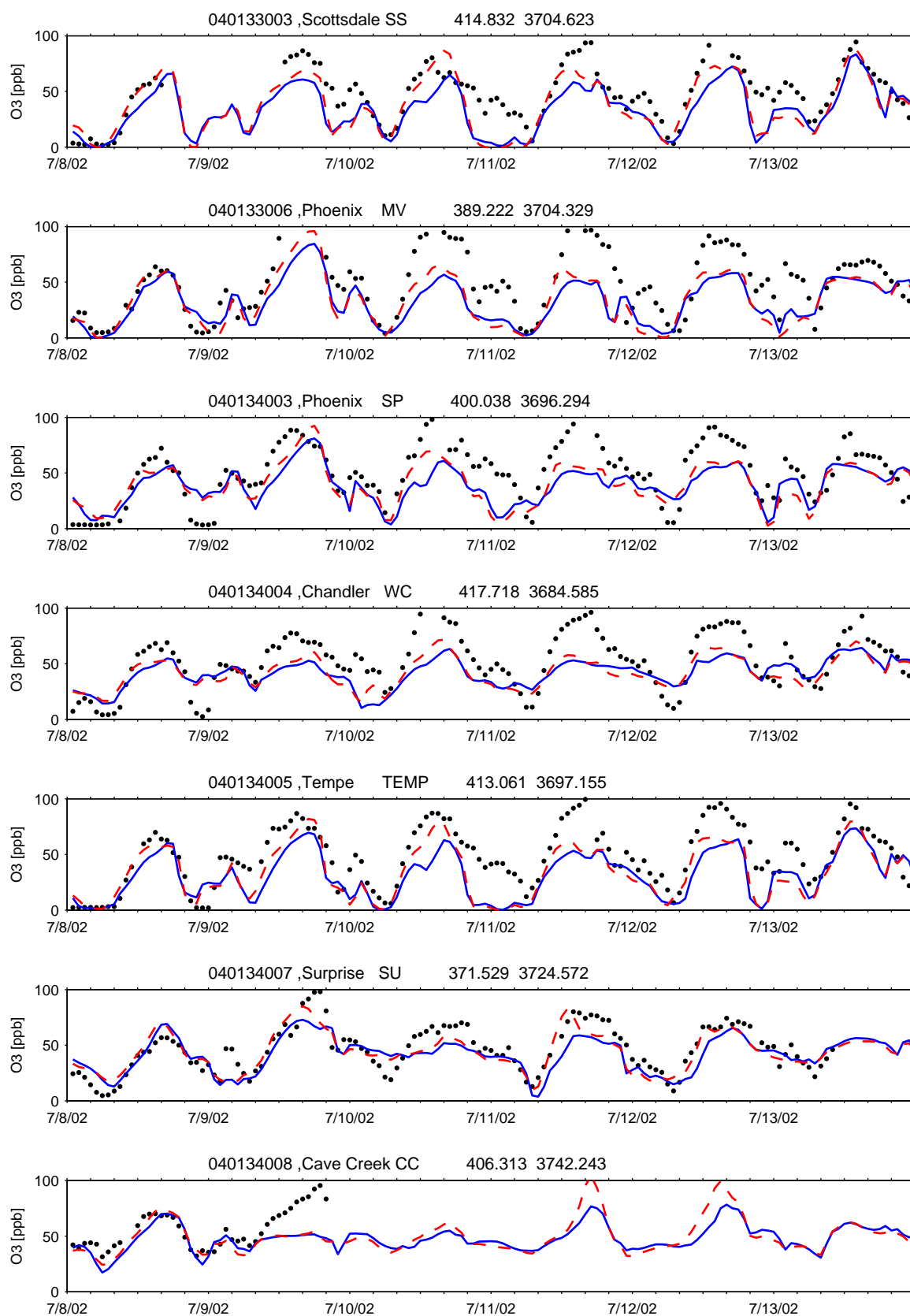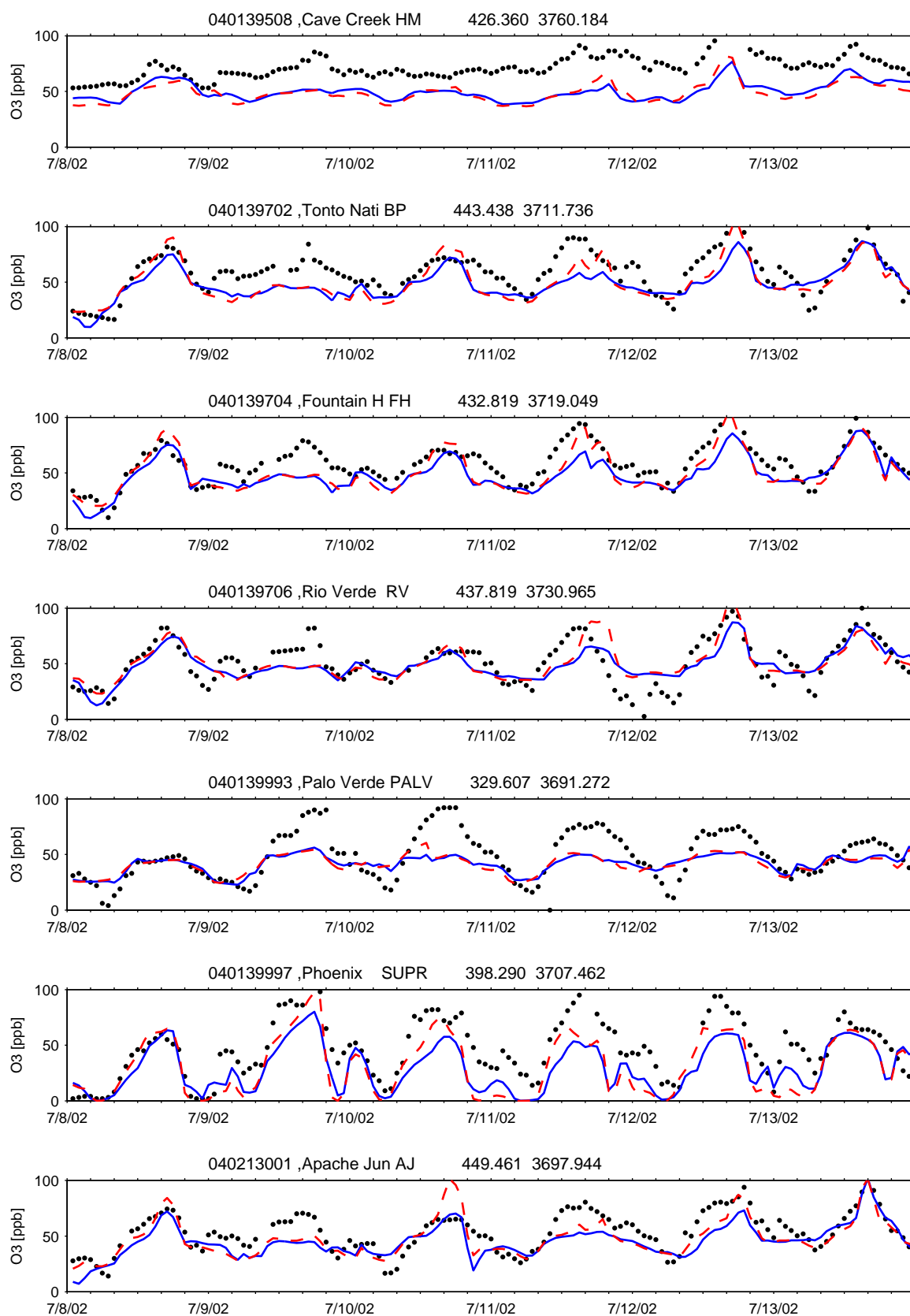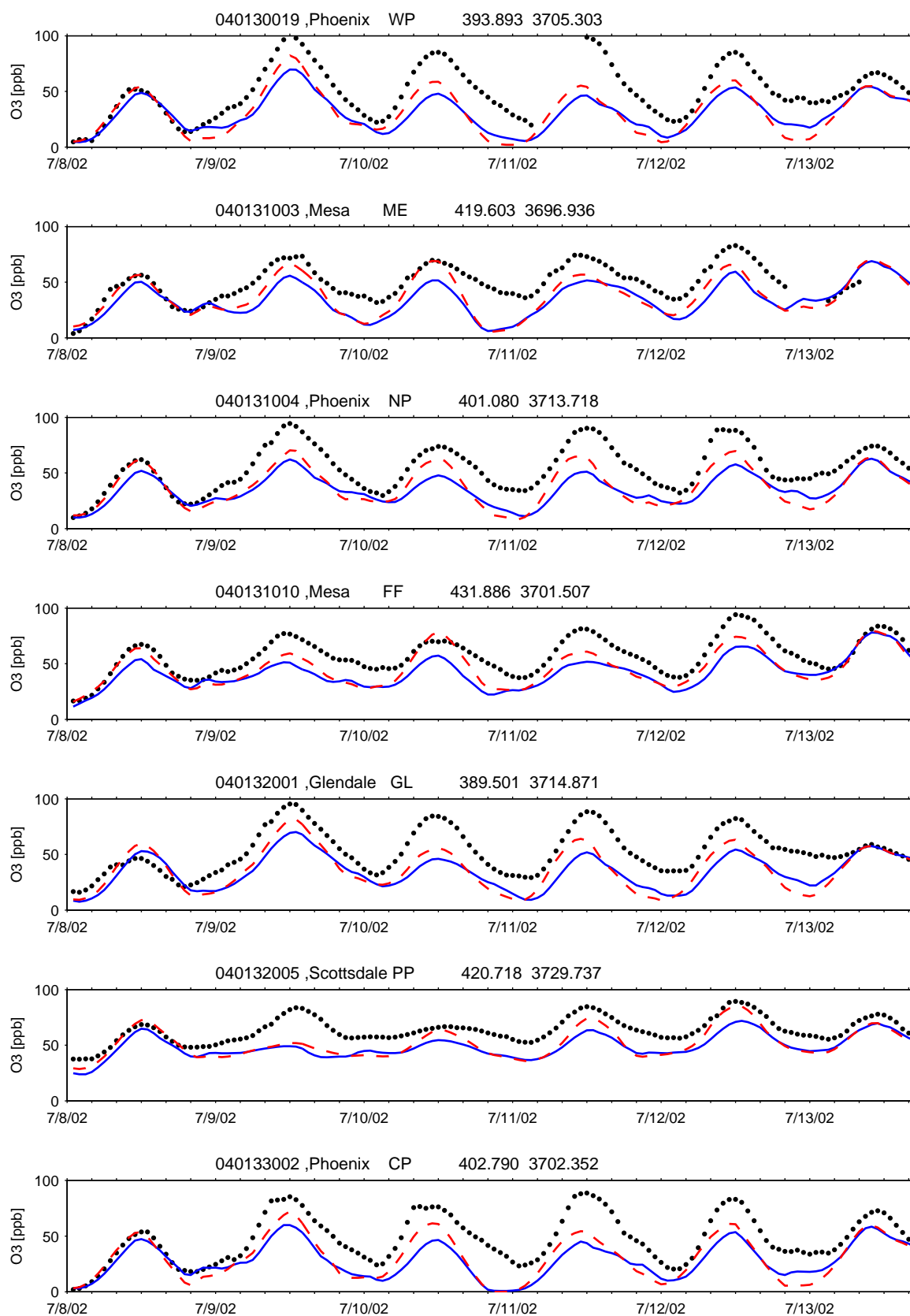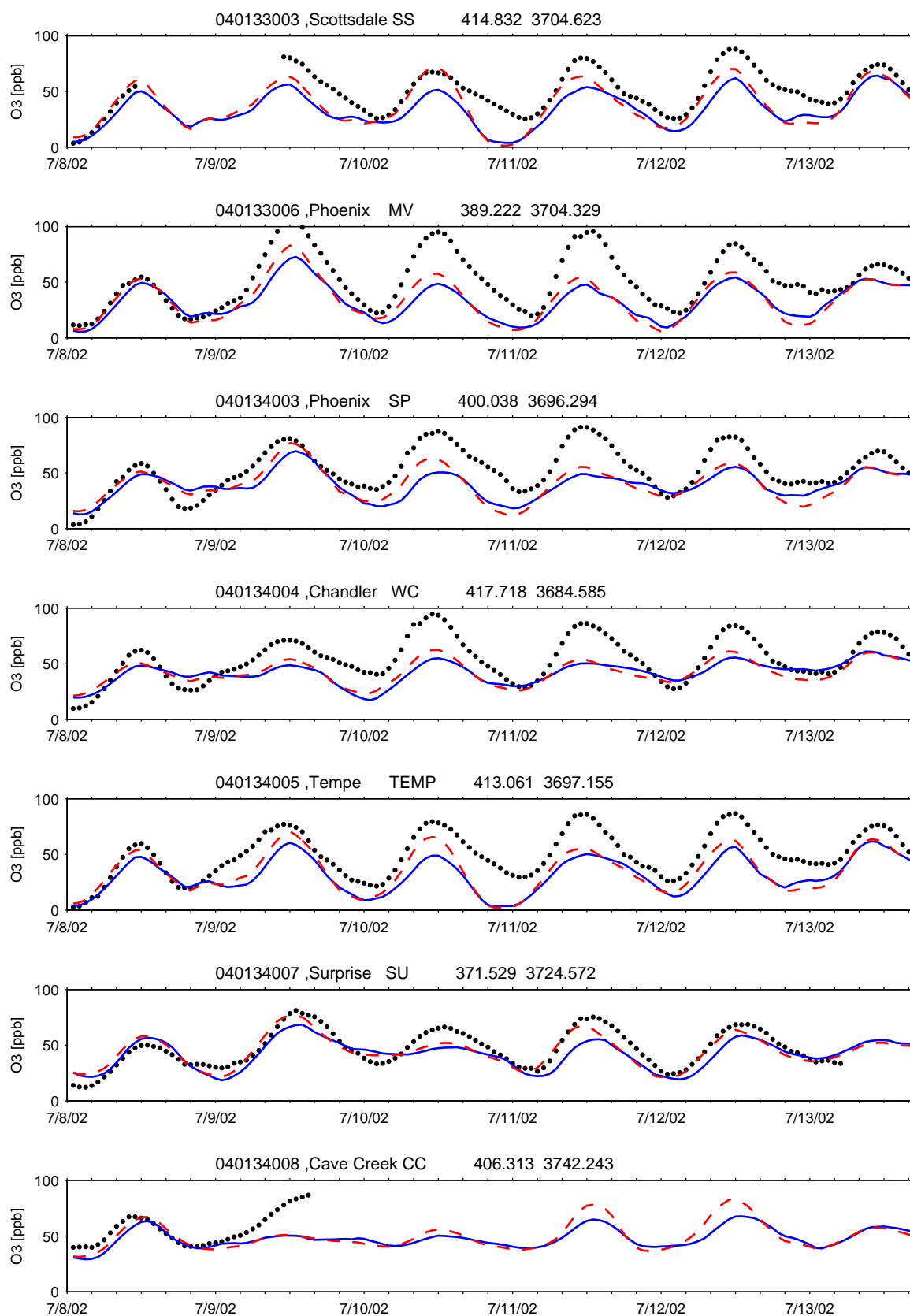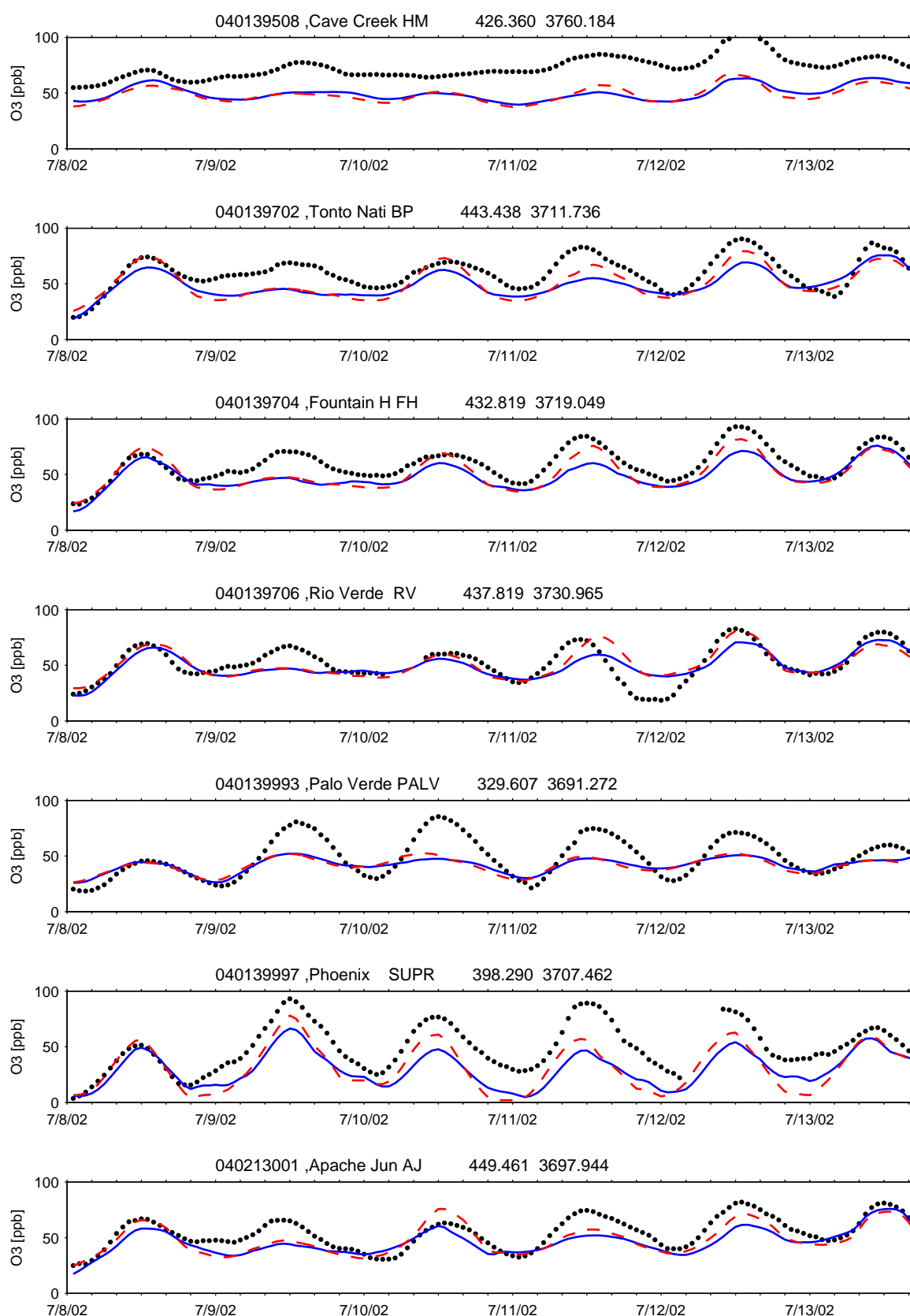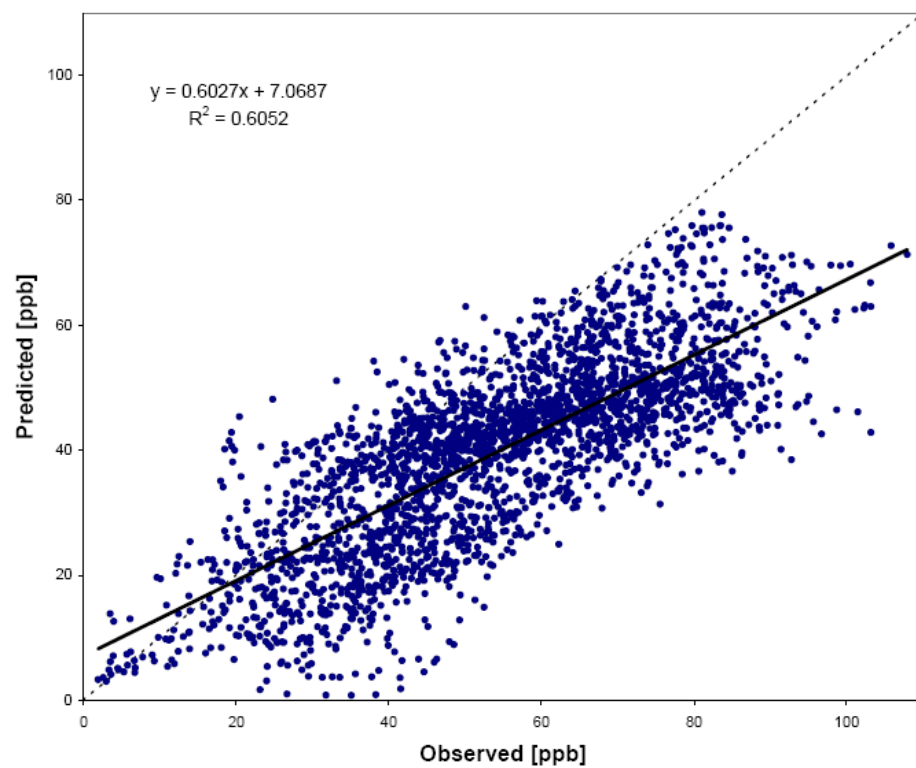
Figure 2(c).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

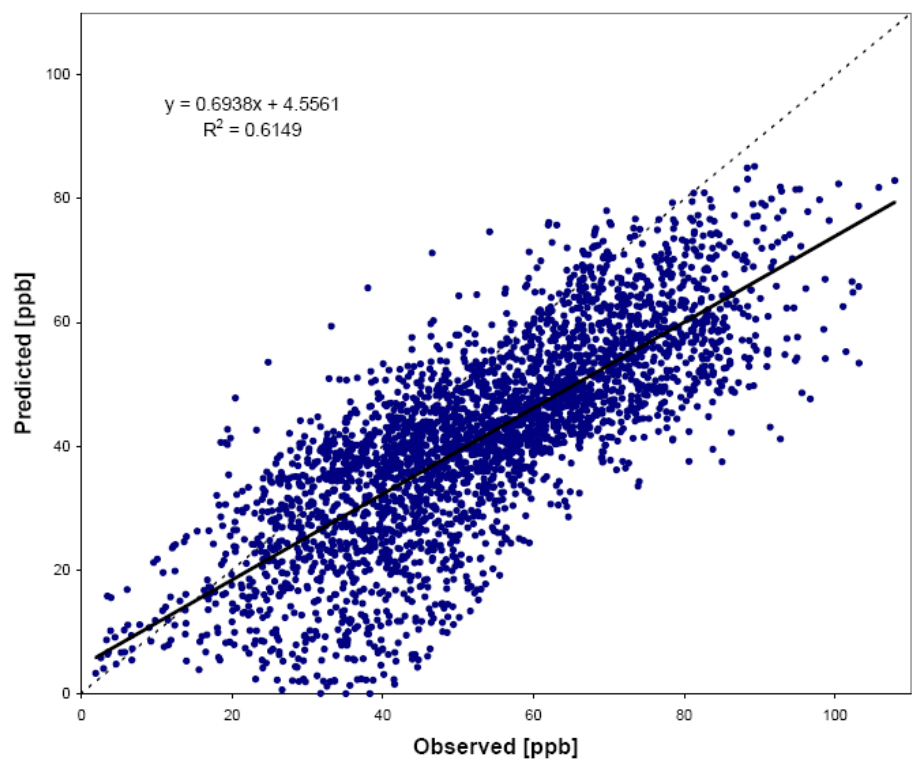Figure 3(a) CMAQ eight-hour ozone in the MNA (June 3-6, 2002)
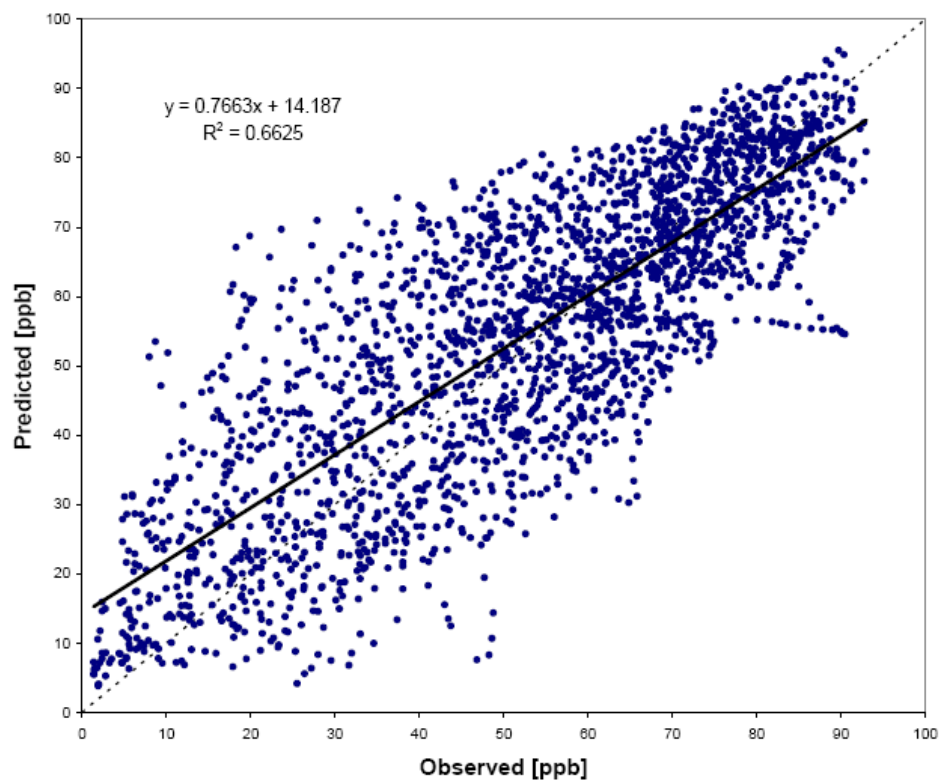
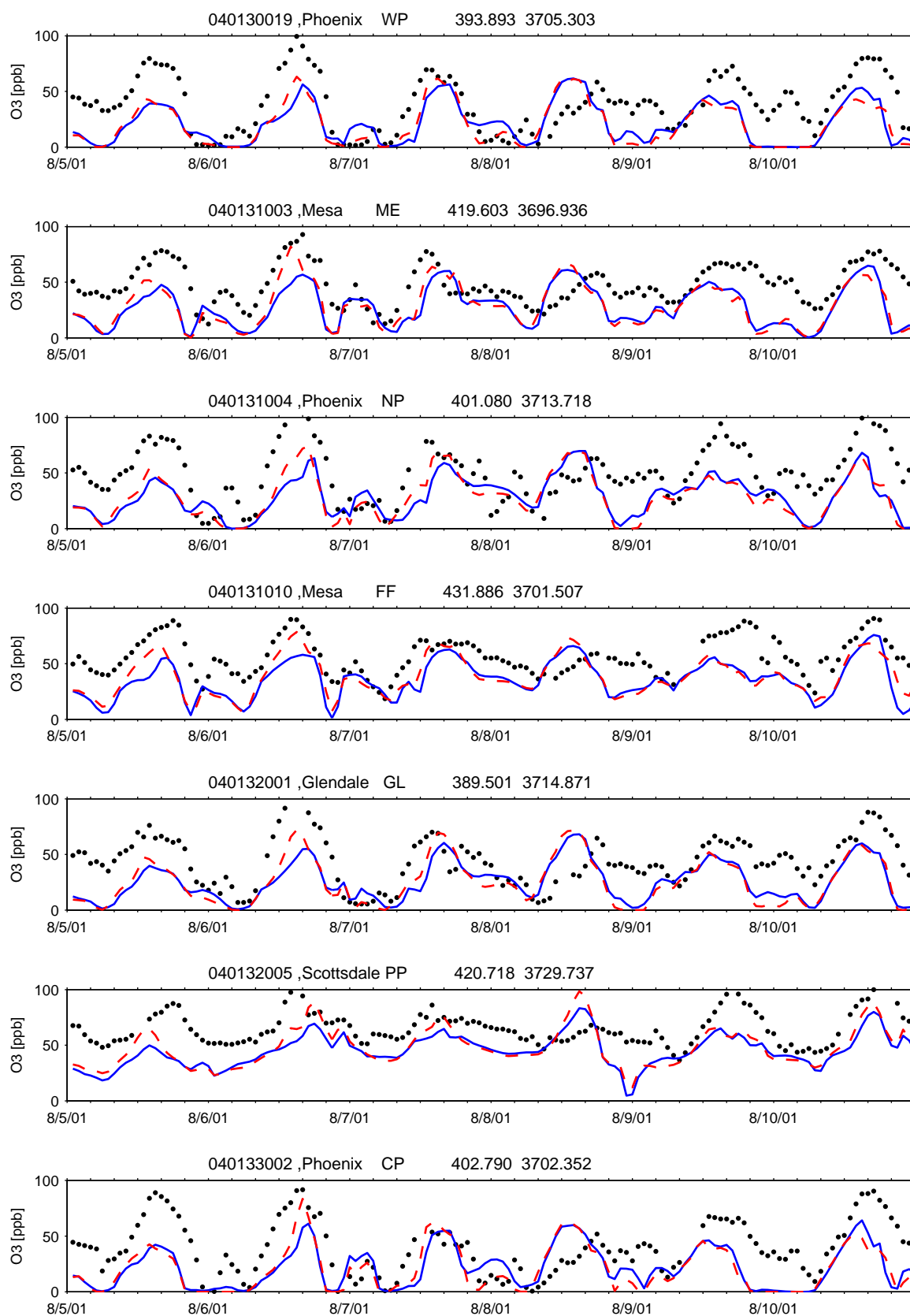Figure 3(b) CAMx eight-hour ozone in the MNA (June 3-7, 2002)

Figure 4(a).One–hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx
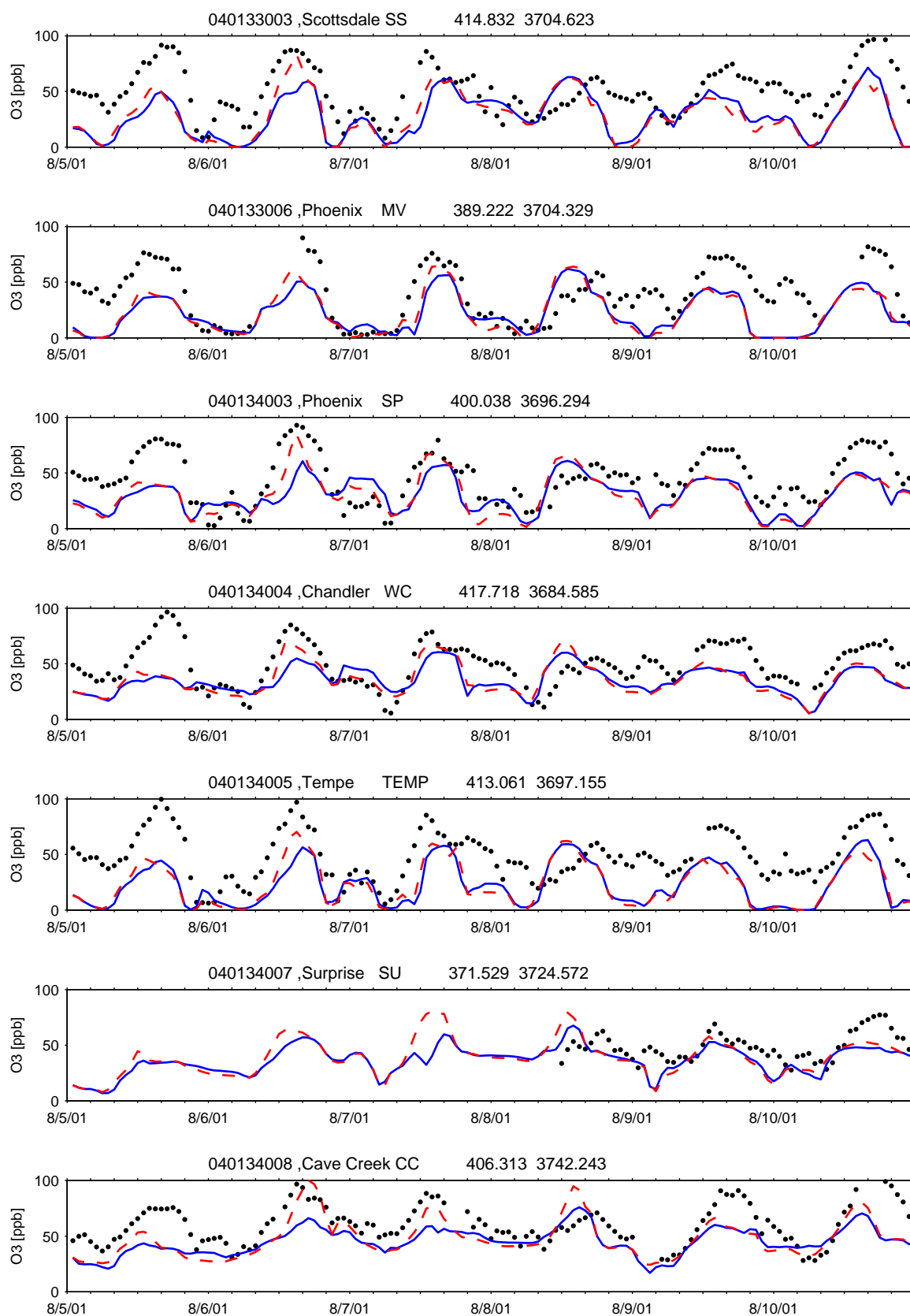
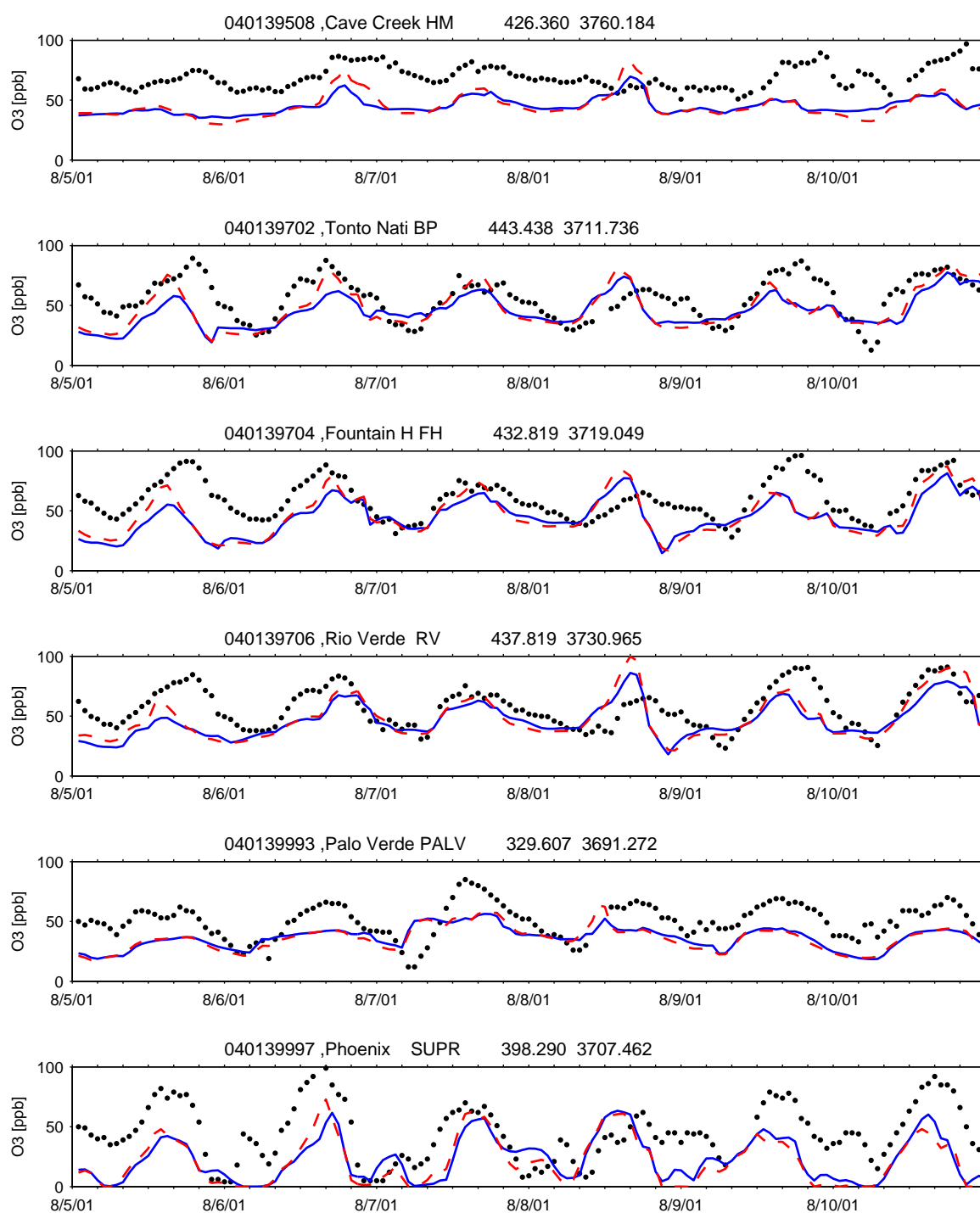Figure 4(b).One−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 4(c).One−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 5(a).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 5(b).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 5(c).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 6(a) CMAQ eight-hour ozone in the MNA (July 8-13, 2002)

Figure 6(b) CAMx eight-hour ozone in the MNA (July 8-14, 2002)

Figure 7(a).One–hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 7(b).One–hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

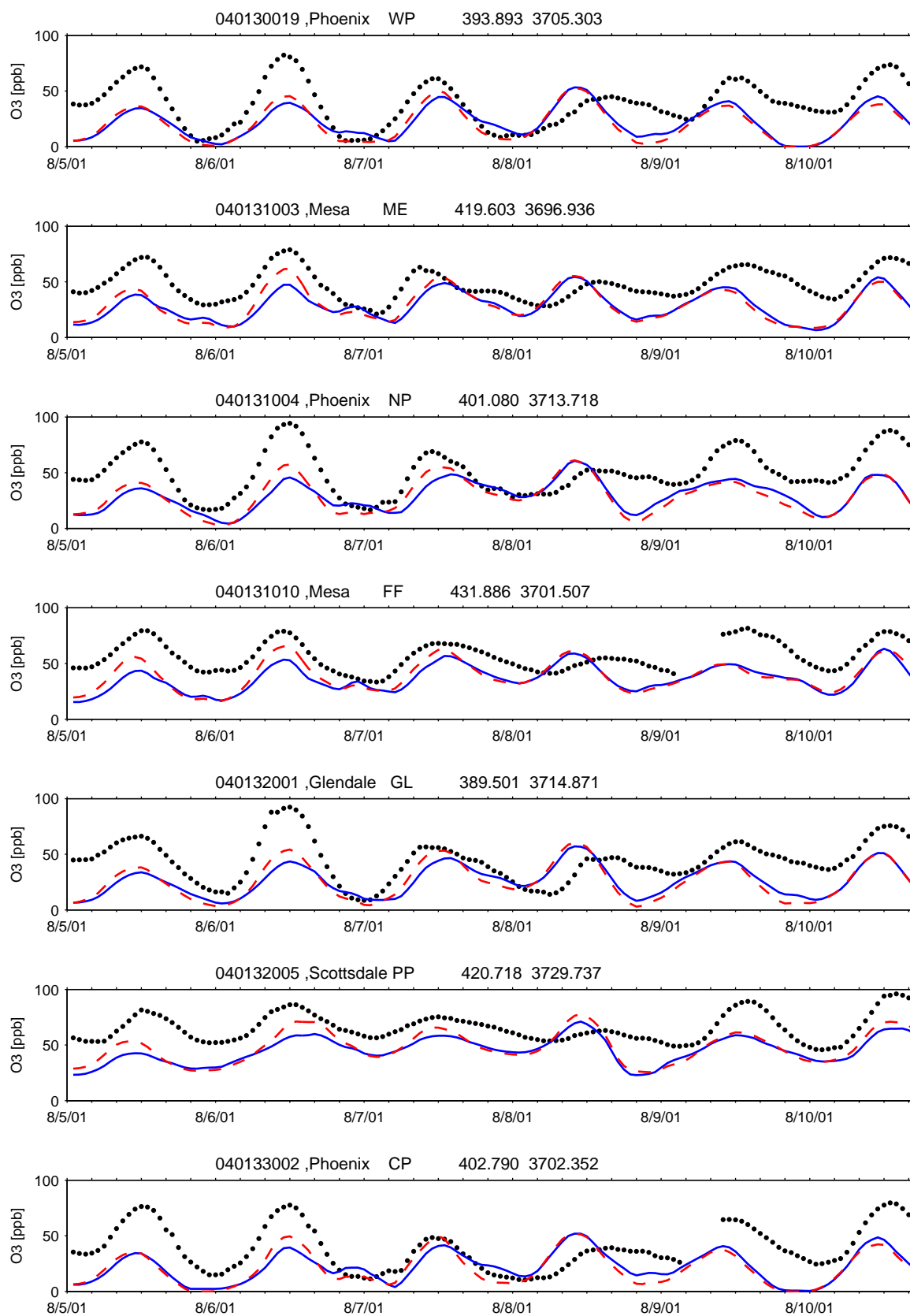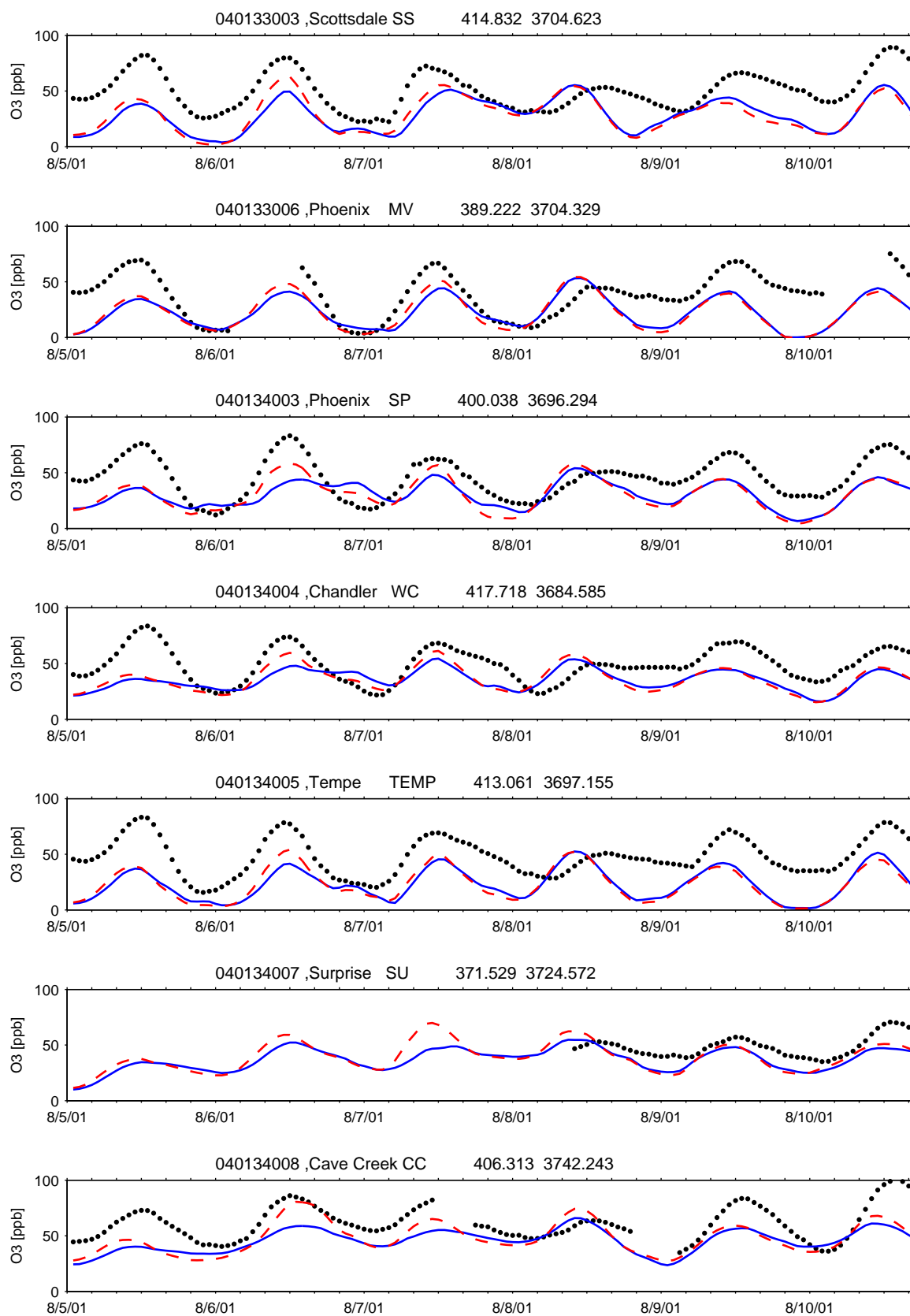Figure 7(c).One−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

040130019 ,Phoenix   WP   393.893 3705.303

040131003 ,Mesa   ME   419.603 3696.936

040131004 ,Phoenix   NP   401.080 3713.718

040131010 ,Mesa   FF   431.886 3701.507

040132001 ,Glendale   GL   389.501 3714.871

040132005 ,Scottsdale PP   420.718 3729.737

040133002 ,Phoenix   CP   402.790 3702.352

Figure 8(a).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx

Figure 8(b).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx
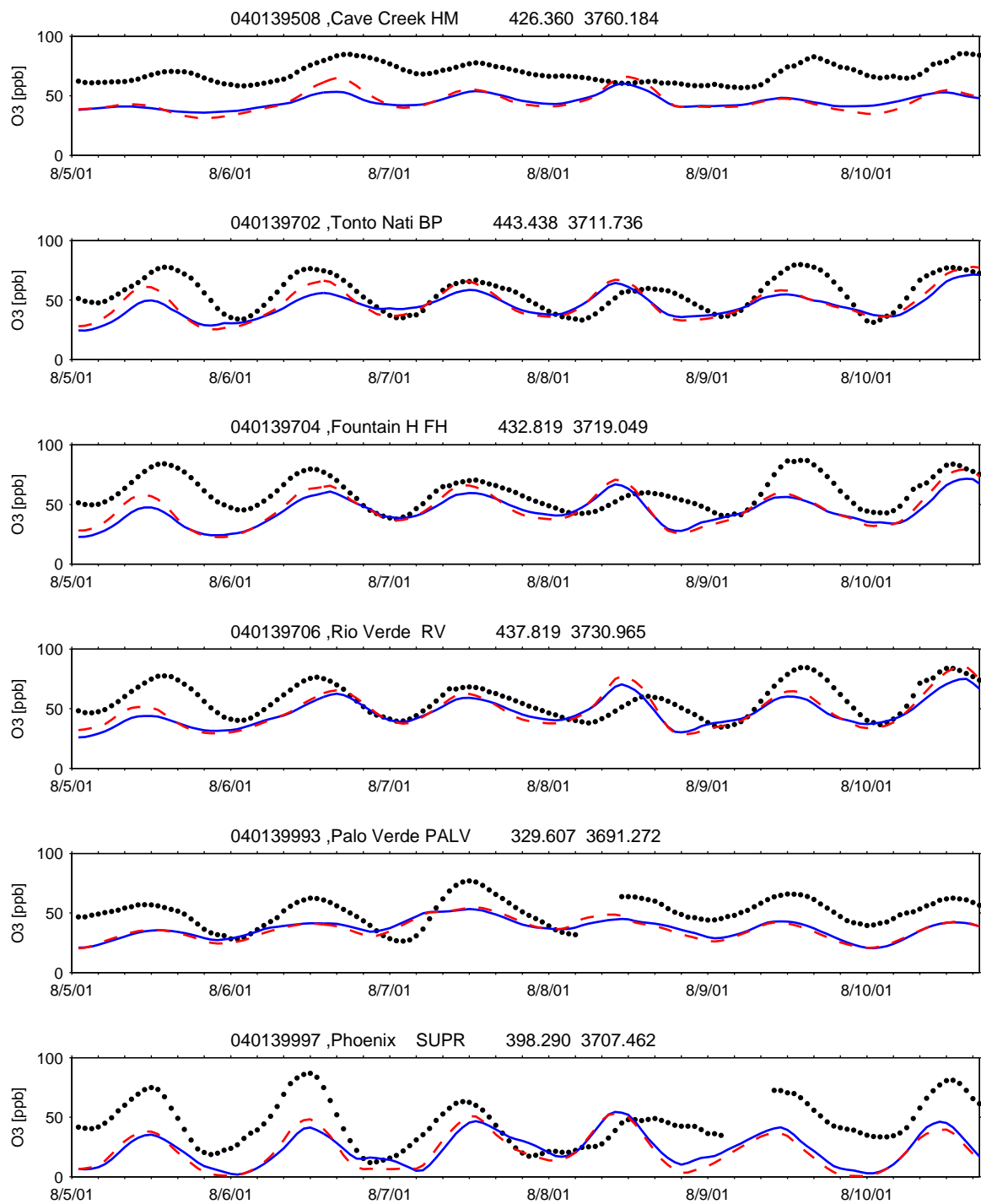
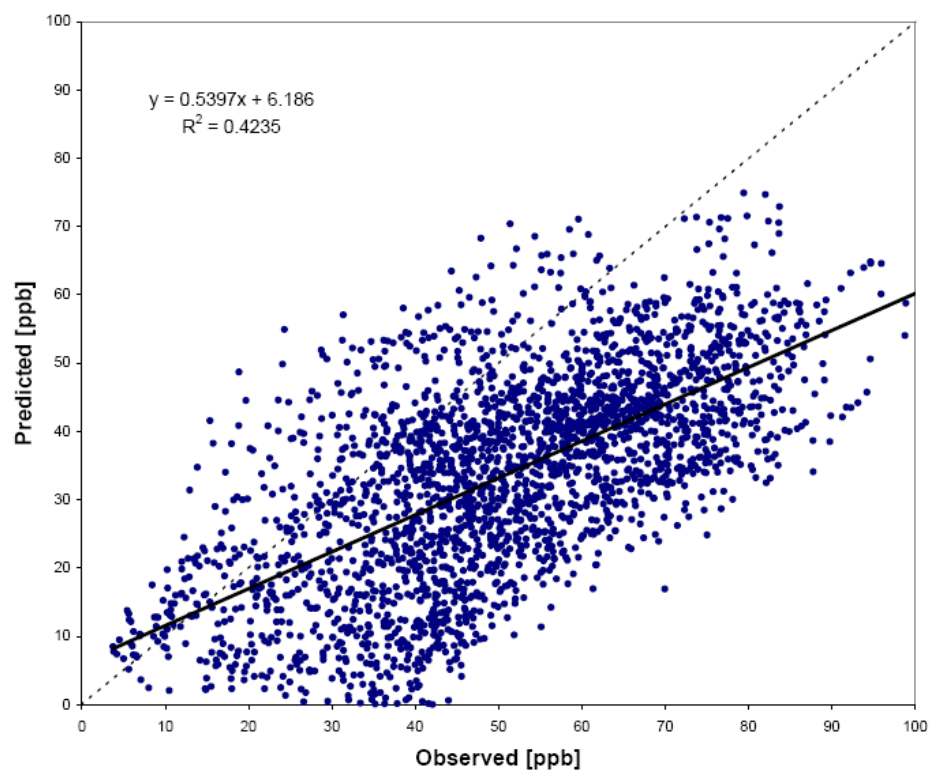Figure 8(c).Eight−hour ozone. dots: observation; solid line: CMAQ; dash line: CAMx
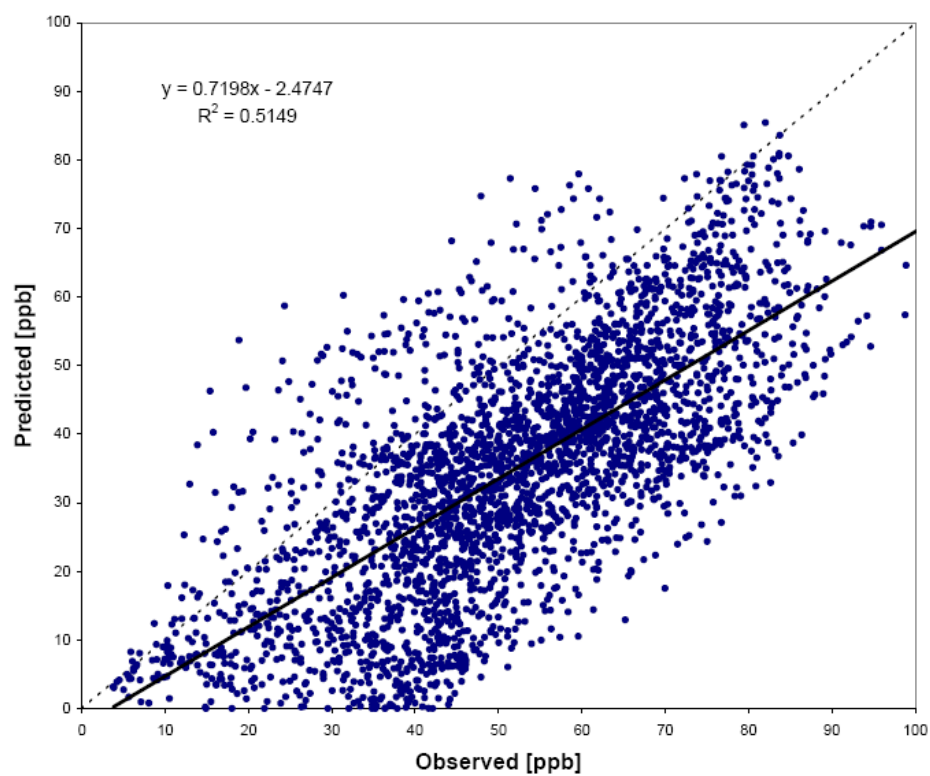
Figure 9(a) CMAQ eight-hour ozone in the MNA (August 5-10, 2001)

Figure 9(b) CAMx eight-hour ozone in the MNA (August 5-11, 2001)